Designing low-emission aero-engines using adjoint methods

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As demand for air transport increases, the need to enhance the aircraft performance and reduce emissions also increases. One route to aircraft engine performance improvement, investigated in this work, is to use the parameters defining features in the CAD model geometry (Fig. 1) as the design variables in the optimization loop. One advantage is that it eliminates the need to recontruct the design model for the purpose of optimization, allowing a more efficient and integrated optimization process. Another advantage of using the feature based model is that the optimized model produced can be directly used for the downstream applications, including manufacturing and process planning.

Adjoint methods have been the subject of considerable research in recent years [1], and can be used to compute the gradient of a large number of design variables at minimal cost. The goal of this work is to present an efficient CAD-based adjoint process chain for calculating parametric sensitivities (derivatives of the objective function with respect to the CAD parameters) in timescales acceptable for industrial design processes. This approach differs from other methods due to the fact that it works with existing commercial CAD packages (unlike most analytical approaches) and it can cope with the changes in CAD model topology and face labeling which hamper similar approaches [2].

The approach is demonstrated on a Nozzle Guide Vane (NGV) of a high pressure turbine (HPT) provided by Rolls-Royce, which governs the engine mass flow (and by association the capacity) and defines the narrowest cross section of the turbine. Optimizing this can significantly reduce the amount of energy required to provide a certain performance.

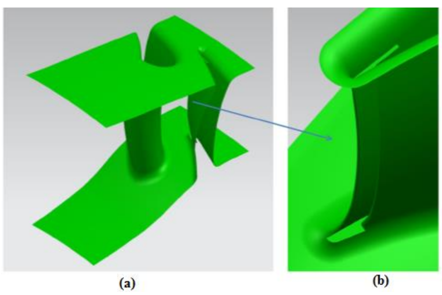

Figure 1 3D parametric CAD model in Siemens NX: a) NGV geometry and b) TE cooling slot

In order to capture the CAD surface movement with respect to the change in parameter value (Δp), the Parametric Design Velocity (V_n) is calculated, which is the movement of the CAD model boundary in the normal direction due to a change in parameter value. The approach herein is a significant enhancement on [3] in terms of the functionality provided, and can be easily integrated into most industrial optimisation workflows. The implementation calculates the design velocity in the normal direction based on projections between discrete representations of the original and perturbed geometry. Parametric design velocities can then be directly linked with adjoint surface sensitivities (ϕ) to extract the gradients ($\Delta J/\Delta p$) needed in a gradient-based optimization algorithm, where

$$\Delta J = -\int \phi V_n dA \qquad (1)$$

A 3D parametric CAD model of a NGV was built in Siemens NX, defined using geometric parameters, as shown in Fig. 2, and capacity is considered as the objective function.

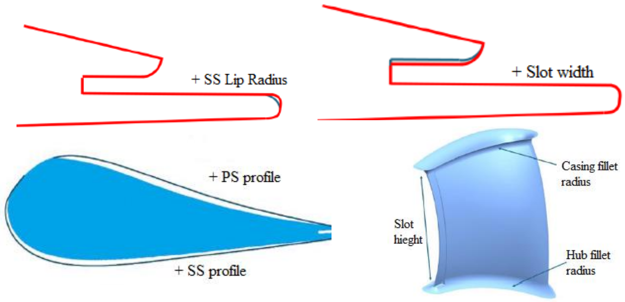

Figure 2 CAD parameters considered as design variables (not to scale)

The change in capacity (improvement in performance) caused by each parametric perturbation is predicted by taking the inner product of the sensitivity map with the corresponding design velocity field fo the parameter. The obtained derivatives are shown in Fig. 3, where they are compared with central Finite Difference values showing good correspondence.

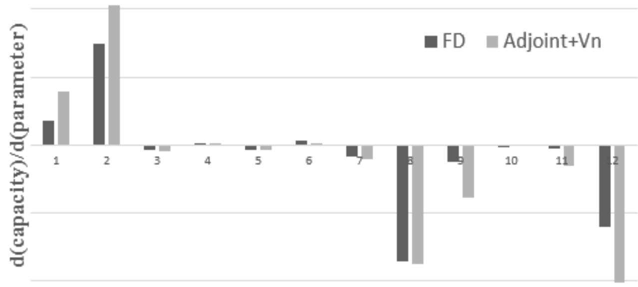

Figure 3 Capacity derivatives predicted by adjoint results and validation against FD

The computational cost to perform one flow analysis takes nearly one day, thus doing a finite difference study would for for the NGV test case (12 design variables) would result in 3 weeks of time, whereas the proposed approach takes only two days (1 CFD + 1 adjoint). The computation of design velocities is done in parallel to the flow analysis and takes only 45 minutes.

References

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